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Anticipation: Beyond synthetic biology and cognitive robotics

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ABSTRACT

The aim of this paper is to propose that current robotic technologies cannot have intentional states any more than is feasible within the sensorimotor variant of embodied cognition. It argues that anticipation is an emerging concept that can provide a bridge between both the deepest philosophical theories about the nature of life and cognition and the empirical biological and cognitive sciences steeped in reductionist and Newtonian conceptions of causality.

The paper advocates that in order to move forward, cognitive robotics needs to embrace new platforms and a conceptual framework that will enable it to pursue, in a meaningful way, questions about autonomy and purposeful behaviour. We suggest that hybrid systems, part robotic and part cultures of neurones, offer experimental platforms where different dimensions of enactivism (sensorimotor, constitutive foundations of biological autonomy, including anticipation), and their relative contributions to cognition, can be investigated in an integrated way.

A careful progression, mindful to the deep philosophical concerns but also respecting empirical evidence, will ultimately lead towards unifying theoretical and empirical biological sciences and may offer advancement where reductionist sciences have been so far faltering.

1. Introduction

The debate on the nature of cognition and the mechanisms that support it has been at the heart of one of the most profound areas of human inquiry. Some researchers and philosophers believe that there is a fundamental link between cognition and living (Thompson, 2007). As opposed to inanimate objects, which are passive recipients of external forces and disturbances, living systems seem to be characterised by their ability to act in the environment in a way that suggests goal-oriented behaviour. One of the characteristics that seem to be underpinning intentional and purposeful behaviour is an ability to act, taking into consideration future events.

Accounting for such intentional states, however, has been very problematic in traditional science, which is mostly dominated by the reductionist and Newtonian conception of causality, implying that physical laws admit state changes of physical objects only on the basis of past and current state. Causality understood in this way has been a sacro-sanct postulate in physics and, following its undeniable successes, has become a broadly accepted axiom across sciences.

Thus, teleology has been largely eliminated, at least from biological sciences, and some thinkers would even go as far as to deny goal-directedness of cognitive agents like ourselves. Others adhere to a computational view of cognition which, consistently with scientific position (currently accepted conception of computing is a classically causal mechanistic paradigm), deems the 'hard problem' as simply non-existent, (Dennett, 1996), or as a mere consequence of sufficient 'complexity' and computational power.

Enactive and embodied cognition propose that the computational account misses an important constituent, the embodiment in lived and living body, in order to provide a full account of mind states.

In response to the dissatisfaction with the purely computational accounts, the next generation of AI efforts broadly subscribing to embodied cognition consider augmentation of the traditional computing paradigm (discrete, symbolic) with robotic hardware body (amounting to analogue, continuous computing), as possessing sufficient explanatory power, at least in principle (O'Reagan, 2007; Haikonen, 2012).

Cognitive robotics has invigorated the enthusiasm in studying and perhaps even recreating at least certain aspects of cognition in purely man-made systems. This growing interest may be partly explained by the seeming balance struck by cognitive robotics. On the one hand it sits well in the embodied cognition framework, whereby sensorimotor accounts offer a natural conceptual framework and justification for this approach. On the other hand, it is still

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firmly tied to hard sciences, thus offering an opportunity to study and understand cognitive processes within an analytic framework.

However, the only truly cognitive system we know of are biological living organisms; an observation which would seem to suggest that the only approaches that can elucidate the most fundamental questions about the nature of life and cognition must involve biological, neuroscience and cognitive sciences. On that view robotic systems can never, in principle, offer satisfactory explanations. Hence, on this account, a cognitive robotics programme must fail where neurobiology and cognitive science prevail.

Nevertheless, the position put forward in this paper is more subtle. Both cognitive robotics and much of natural science share a common philosophical framework tantamount to a very mechanistic view of the world. We propose that this commonly inherited framework underlies common difficulties any of these approaches would have, when trying to provide an account of autonomous behaviour or intentionality. This is because there seems to be a deep chasm between our system of knowledge based on traditional science and our subjective experience, in light of which the ability to anticipate the future, and act on it, appears to be a rather basic property of agency in general and specifically of human agency.

We propose, largely following theoretical biologist Robert Rosen, that anticipation is one of the most fundamental characteristics of living, cognitive systems and that its proper account necessitates reframing the usual notions of causality and mechanism. In fact, although on the surface it may seem that anticipation requires the presence of a sophisticated cognitive system, forms of anticipatory behaviour have been observed even in unicellular organisms. It is altogether not too surprising, because the ability to modify behaviour in anticipation of the future may offer an adaptive advantage to organisms possessing it, thus may putatively playing a role in evolution.

In consequence, two questions arise. Firstly, what processes allow for anticipation to occur? And secondly, are there any common principles underpinning anticipation across different levels of organisms' complexity? Understanding such processes is interesting from a fundamental perspective as it may shed further light on the relationship between life and cognition and also for pragmatic reasons, as it may help us in constructing artifacts with an increased level of autonomy and robustness.

This paper will review some evidence pointing to processes and principles that may offer promising first steps towards our understanding of how anticipation could be realised in biological organisms. Moreover, they could help to reconcile much of traditional science with the notion of anticipation, following in the footsteps of researchers such as Rosen (2012), Louie (2010, 2012), and others, who laid the foundations for our understanding of anticipation. Hence, the answer to the original question of whether cognitive robotics or biological and cognitive sciences are more suited to characterise the most fundamental properties of living systems is neither of them, as long as they remain confined to the mechanistic explanations. Although it seems that cognitive robotics is thus bound to fail, more recent developments in the form of hybrid systems, animats, constituted by cultures of biological neurones embedded in a closed loop in robotic bodies, offer a possible way forward whereby robotics may still be relevant to elucidate such most fundamental issues.

The rest of the paper is organised as follows. Section 2 will discuss how cognitive robotics, building partly on Artificial Intelligence and partly on cybernetics, continuing the development within sciences of tries to provide a mechanistic account of cognition.

Section 3 will review some theories linking life, cognition and anticipation. The next section, Section 4, will discuss the evidence of anticipatory behaviour in organisms.

An approach that may help cognitive robotics to make steps beyond its mechanistic confines, is to use animats, part-machine part-biological hybrid entities. The animat platform is the focus of the penultimate Section 5. The conclusions end the paper with some caveats.

2. From scientific to cognitive robotics accounts of cognition

The attempts to clarify the nature of processes underpinning life and mind have often been pursued independently. This is especially true within the traditional reductionist science paradigm, which tries to isolate the properties in question and to understand them by reducing the above to their primary components. However, in spite of undeniable successes of modern science and medicine, these two problems have so far defied such an approach. It seems that as soon as we start concentrating on individual components and characterise their function mechanistically, we loose sight of the bigger picture and fail to notice that a mechanistic explanation may not be able to account for the highest level of organisation. Thus, within reductionist, mechanistic science paradigm we are then left with a dilemma – either accept that there is nothing more to living or sentience than mere mechanisms (albeit complicated ones) or abandon these questions altogether. The amalgamation of the two stances has characterised the mainstream science position at least since biology and psychology started to aspire to achieve the level of mathematical rigour enjoyed in XIX century physics.

The mechanistic tradition was somewhat continued in approaches rooted in Alan Turing's formalisation of computing operations. Turing wanted to provide a mechanistic minimal definition capturing the essence of operations performed by, then human, computors engaged in highly repetitive tasks used at the time for performing nontrivial calculations. A modern computer was born of these efforts and the Turing Machine (TM) now provides one of the most fundamental definitions of classical computing. The TM was a reflection of the mere fact that the cognitive system's (human computor) ability to follow formal rules can be successfully encapsulated in such a minimal formal mechanism. When combined with an enthusiastic belief that computers can compute anything worth computing (aka Church-Turing hypothesis), this led to a conclusion that the TM can account not only for cognitive system's ability of following formal rules but in fact for the entirety of cognition. Basing cognition on the TM paradigm seemed to have offered a step in the right direction, reuniting the science of human psyche with hard sciences, as the TM presented a quintessentially mechanistic and reductive explanation. Thus, cognitive science and its close cousin, artificial intelligence, incorporated the TM, or formal manipulations of symbol systems within their modus operandi. The outcome of this was that the description (computation) of a very specific phenomenon (formal rule following by humans) was conflated with the phenomenon itself. Although, a distinction between an object and its description is clear and unquestionable in almost every other scientific domain, large part of cognitive science have accepted this conflation without much reserve.

Such approaches were soon opposed by various thinkers who were not satisfied with the perceived shortcomings of the formal symbolic approach to explain fundamental properties of cognition. Many of such criticisms grew out of methods, which at the height of its popularity were the domain of cybernetics, or which later could trace their heritage to cybernetic movement. The critics emphasised the importance of continuous time and state space evolution, and decentralised nature of biological processing; features which were at odds with the computational paradigm. Yet, important caveats as they were, they did not address the fundamental shortcomings of the computational symbolic account as discussed

at length in the seminal work of Searle on an infamous Chinese Room argument (Searle, 1980). The ensuing heated debate continued for years, as evidenced in Preston and Bishop (2002), with neither Searle nor his opponents able to convince the antagonists to accept their arguments.

The reason for such a failure might have been that computer science and cybernetics grew out of the same scientific milieu – an attempt to provide a general framework, which nevertheless fell back on the traditional scientific account based on reductionism and classical mechanistic explanation rooted in Newtonian take on causality.

Similarly, further objections in the form of a 'robotic reply', as presaged by Searle, did not fare any better against Searle's rebuttals. These debates were still framed in a very computational framework.

More recently, the cognitive robotics agenda received more support in the form of a growing movement in cognitive science, enactivism, recognising that strict cognitivism is not satisfactory and that the biological body may play an important role in cognitive processes. Enactivism is not a unitary position, with the amount of emphasis on how important the body is and what role it plays in cognition being one of the differentiating characteristics of its various forms. Cognitive robotics seems to gain particular traction with a flavour of enactivism, embodied cognition, which proposes that "our ability to perceive not only depends on, but is constituted by our possession of [...] sensorimotor knowledge" (Noe, 2004). The claims that "cognition relates to sensorimotor interactions rather than to material self-constructing processes" (Barandiaran and Moreno, 2006), and that "the structure of sensorimotor contingencies" provides a link to Gibbsonian affordances were particularly appealing for cognitive robotics as they appeared to furnish it with a grounding in modern cognitive science.

O'Reagan claims that a sensorimotor account provides a satisfactory account of phenomenal experience that can be integrated with (traditional) higher order cognition to provide a complete account of conscious experience (O'Reagan, 2007). As a consequence, we should be able to construct robots that are conscious.

Interestingly, recognition of the importance of body for active exploration and inference has also led to confluence of the embodied cognition with predictive brain hypothesis, (Clark, 2015), which frames the inference problem as an active process where brains constantly attempt to predict the sensory streams. One of the strongest proponents of predictive brain and active inference hypothesis is Friston et al. (2010). The predictive brain hypothesis has also been extended to include some aspects of social cognition (Otten et al., 2016).

A number of approaches within the cognitive robotics community are consistent with the above mentioned developments stressing the importance of prospection, (Vernon et al., 2015), prediction, (Zambelli and Demiris, 2015), or active exploration via reinforcement learning, (Merrick, 2010), and curiosity-driven or active learning (Forestier and Oudeyer, 2015).

However, the air of legitimacy offered to cognitive robotics by sensorimotor or embodied prediction accounts is illusory. The problem is that embodied cognition that reduces body to a mere physical instantiation of sensory motor loops does not go deep enough in acknowledging the importance and implications of the biological embodiment for cognition. If the role of the biological body (including the nervous system and the brain) merely provides a wet-ware implementation of the sensorimotor loops, one needs to ask what in principle is the difference between such 'patterns in the structure of sensorimotor contingencies' and any patterns in sensory data. On this interpretation of embodied cognition the body amounts to a part of a sensorimotor closed loop between neural activity responsible for bodily (motor) action and the activation of neural populations in the sensory areas resulting from such an action. As the role of the body has been reduced to a conveyor of closed loop activity, the essence of the explanations resting solely on sensorimotor loops must therefore be confined to causal interactions between motor and sensory neurone populations activated by the results of the actions instantiated by the sensorimotor loop. But why should such causal interactions between two neural populations be any different from any other causal interactions between other neural populations, e.g. between neurones in two sensory modalities. If the operations of neurones can be explained away with activation flow via trains of action potentials (or any other variable that is solely meant to be involved in neurone information processing capacity), the causal interactions of the sensory and motor neurones do not seem to have any privileged position in comparison to analogous interactions between any other neuronal populations. The other possibility is that other bio-physico-chemical properties of a body, including the neurones supporting the sensorimotor loop, must be somehow involved, such that the operation of the sensorimotor loop is inexorably linked with the biological (metabolic) makeup of cells constituting it.

Cognitive robotics stops where such restricted version of embodied cognition does. By concentrating on providing a grounding exclusively in the external world, it can capture its relational structure, however, the same can be achieved by correlations and look-up tables. Thus, cognitive robotics does not fare much better than computational accounts. Adding extra sensors or actuators, or even using different formalisms, be it symbolic, dynamical or connectionist, to drive the robotic platforms' closed loops, does not improve the situation, as these simply result in different forms of capturing the relational structure of the external world.

This may be understood if one considers that the robotic embodiment of an otherwise computing machine, renders the entire system a part analogue, part symbolic hybrid, and as such still falls within a broad conception of computing (Spencer et al., 2013).

Similar concerns have been raised by Ziemke et al. (2014), Ziemke and Thill (2014), who inquires about ascribed ('as if') and intrinsic intentionality. He claims, after Harnad, that cognitive robotic research constitutes an extension of classical computational functionalism to robotic functionalism. Thus, current robotic technology cannot really equip robots with true intrinsic intentionality, unless one believes that strict sensorimotor theory provides its satisfactory account.

Although the reservations discussed in previous paragraphs have been leveled at accounts justifying cognitive robotics on the basis of sensorimotor theory, they equally apply to cognitive robotics systems that may use predictive forward models in their control. As Bickhard argued, (Bickhard, 2016), predictive computational theories cannot provide a full account of cognition in living bodies, neither can they help cognitive robotics escape criticisms of mechanical vacuity. As Nadin argues, prediction or expectation do not equate to anticipation, (Nadin, 2013), and it is the latter that holds special place in some theories of biological autonomy (Rosen, 2012; Bickhard, 2016). Moreover, in one of a few formal derivations in this domain, Louie proved that anticipation is a necessary but not a sufficient characteristic of living systems (Louie, 2012). Thus, it is not a mere matter of presence of anticipation (let alone prediction or expectation) that solves the problem; it is how it is realised by a system of appropriate complexity (it must, following Rosen and Louie theory, also be impredicative, i.e. containing a closed path of efficient causation) that is at stake.

In contrast, even the simplest biological organisms have internal drives at all levels of organisation: organismic, metabolic and physical. These make them act in the world, with such processes constituting, driving and modulating activity of all building blocks of the closed interaction loops in ways that result in such sensorimotor interactions that will support immediate and delayed fulfillment of the drives at all levels.

Intentionality comes not only from the potential mapping between relational structures of the external world and the states of biological constituents, but also from relation between such structures and internal drives and needs of an agent.

Systems that are based on formal manipulation of the internal representations are thus neither intentional nor autonomous, as no manipulation is internally driven nor serves an intrinsically meaningful purpose other than that of the system's designer.

3. Life and cognition – from autopoiesis to anticipation

Apart from sensorimotor theory variant of embodied cognition or broadly construed enactivism, a number of theories have appeared, more often arising at the interface of philosophy, cognitive science and theoretical biology, embracing the body as more than a mere passive vessel rendering the computational mind with analogue computing capabilities. They posit that biology of the living systems is inexorably linked with cognition and both require a fundamentally different approach from a traditional mechanistic methodology, in order to provide their truly satisfactory explanation. There are a number of such accounts and the field is still quite fragmented, because these efforts have been put to address specific and distinct problems and often stemmed from different fields. As such, they are defying a neat classification in terms of the underlying discipline, which is probably not surprising given that the problem they tackle cuts across the traditional scientific domain silos.

In order to facilitate their discussion, the material in this section is structured around different characteristics and the extent to which relevant theories relate to them. Specifically, the first two paragraphs attempt to draw readers' attention to the broad similarities between enactive accounts and those rooted in the constitutive biological account of autonomy. The third and fourth paragraphs introduce autopoietic enactivism of Maturana and Varela and theories of Bickhard, Deacon, Kauffman and Rosen paying particular attention to their respective roots and motivations as well as intellectual frameworks from which they arise. Introduced in different contexts and for distinct reasons they are discussed at different levels of abstraction making it particularly challenging to provide a detailed account of their mutual relationships. Nevertheless, some commonalities and differences are discussed in the remaining part of the section with respect to the different levels of explanation and complex structures invoked in these theories.

Autopoiesis, a characterisation of life developed in theoretical biology by Maturana and Varela (1980), has been elaborated further by Varela and his followers into what is now known as autopoietic enactivism in cognitive science (Thompson, 2007). Mark Bickhard developed his interactivist model within a philosophical framework consistent with his own process philosophy (Bickhard, 2016). Terrence Deacon, dissatisfied with the inability of the physical and biological approaches to account for the mental content and subjective experience, proposed a theory spanning biology, biosemiotics, complex systems and thermodynamics (Deacon, 2011). In contrast, theoretical biologist Stuart Kauffman, starting from the quest to understand the origins of life, developed the theories based on complex systems, metabolic regulation networks and thermodynamical considerations and recognised the link between the fundamental properties of living systems and cognition, in the form of autonomous agency (Kauffman, 2000).

Of particular interest in this paper is the work of Robert Rosen, who started formulating his own accounts of living systems using the framework of relational biology (Rosen, 1991, 2012). His (M,R)-system (metabolism and repair) is a relational model in which the functions of metabolism, repair and replication are "closed to efficient causation" – a property that seems analogous to Maturana and Varela's organisational closure (Thompson, 2007). Whereas Rosen's (M,R)-system definition focused on properties of living systems related to Aristotelian material, efficient and formal causes (closure to efficient causation), his other, more abstract model of living, anticipatory system, was concerned with Aristotelian final cause. Thus, according to Rosen, anticipatory systems are systems able to generate internal predictive models of themselves and their environments and use them in order to prolong their existence. As Kineman states in his contribution to the second edition of Rosen's seminal volume (Rosen, 2012), Rosen equated the (M,R)-systems with anticipatory systems, although the work by Louie (2012), suggests that the relationship between these models may be more involved and the (M,R)-systems can be anticipatory under some specific conditions.

The above is not meant to be an exhaustive account of all the approaches to characterise living systems nor does it reflect the amount of further research elaborating the ideas put forward by these pioneers. It also is beyond scope of this paper to discuss in any depth these theories or their mutual relationships. Even this brief account illustrates that the field is still quite fragmented and the individual positions are still often subject to change (for example there have been many different flavours of autopoietic enactivism, which itself is quite distinct from the initial Maturana's account). Thus, Ziemke discusses five different types of embodiment: structural coupling, historical embodiment, physical embodiment, organismoid embodiment and organismic embodiment (Ziemke, 2001). Chemero's distinction between at least two types of embodied theories; radical embodied cognitive science committed to anti-representationalism and anti-computationalism and the more widespread but more narrowly understood sensorimotor account, is discussed in Ziemke et al. (2014). As Froese points out (Froese and Sierra, 2015), in his review of the recent monograph on modern sensorimotor theories, (Bishop and Martin, 2014), the initial sensorimotor theory of O'Regan and Noë evolved into two accounts championed by these authors in later years, in addition to autopoietic enactivism or radical enactivism. As Froese states, more work is needed to provide a detailed landscape of sensorimotor and enactive theories.

Moreover, all of the approaches discussed so far differ with respect to the level of formalism with which they have been developed. Enactive formulations are often very general and not based on a predefined formalism. Similarly, Bickhard and Deacon formulate their accounts in terms of general physical principles and biological mechanisms. Kauffman based his thinking on notions from thermodynamics and complex systems theory but also stated that certain aspects are nonmathematisable. Rosen's accounts are probably most formalised, in that relational biology relies heavily on the category theory. Most of these accounts have been developing in relative isolation from each other, although more recently some work on characterising their interrelationships has started to emerge, e.g. Letelier et al. have discussed the relationship between autopoiesis and (M,R) systems (Letelier et al., 2003).

Nevertheless, in spite of this fragmentation it is worth noting some of the apparent similarities. All mentioned theories are relational in that they recognise that the fundamental properties of biological systems depend on their specific organisation. For Bickhard this amounts to a requirement that a system is recursively self-maintaining. Maturana and Varela emphasise the importance of organisational closure, whereas for Rosen it is closure to efficient causation. Thus, all recognise the fundamental circularity of the organisation of living systems and all agree on the inadequacy of computational accounts of life and cognition.

All theorists invoke various complex systems' structures in order to specify such circular logic of life organisation. Rosen, similarly to Maturana and Varela, concentrates on the biological dimension of such structures consisting of metabolic, reconstruction (repair) reactions, whereas Bickhard, Deacon and Kauffman,

while attentive to biological reality, emphasise also the complex physical phenomena driven by thermodynamic principles which underpin these biological processes. Both Kauffman and Deacon propose that a physical notion of work must play a fundamental role in the emergence of living systems, as the work is involved in energy flows between the system and its environment, and is only possible thanks to operating within certain constraints, which enable the channeling of energy into a 'useful' form. The circularity stems from the realisation that the very constraints needed for work to occur, in turn themselves can only come to existence via work. Bickhard maintains that at the fundamental level the living systems are far from thermodynamic equilibrium systems of a specific type, namely recursively self-maintenant systems. Deacon, consistent with Bickhard, pays a lot of attention to Aristotle definitions of causality, and is concerned with explaining how life emerges from nonliving processes. Recognising the need to provide an account of the Aristotelian final cause, he proposed a hierarchy of complex systems with thermodynamics at its base, in which each next level emerges from the lower level.

In different ways, and often using different language, these researchers agree on the inadequacy of classical science, based on mechanistic conception of causality and reductionism to account for existence of sentient beings with subjective experiences. They also try to reconsider the concept of causality, pointing to circular causality of biological/living systems and anticipation emerging from such processes.

Bickhard perhaps most explicitly makes the link between low level physical processes and anticipation. His far from thermodynamic equilibrium, recursively self-maintenant systems entail, at the most basic level, a capacity for anticipation and hence normative function and these serve the perpetuation of the self-maintenance of such systems (Bickhard, 2009). Thus, Bickhard places anticipation at the basis of the emergence of normativity and ultimately representation, laying foundations for the subsequent explanation of sense making. Thus, normativity is a consequence of symmetry breaking implied by the consequence of anticipation; the system will perform an action that will support its maintenance of far from equilibrium state or otherwise it will start falling into equilibrium, thus will cease to exist. Bickhard (2016), contrasted his interactivism with autopoietic enactivism. The thrust of his critique is aimed at autopoietic enactivism as he contends that the focus on internal self-production in autopoiesis is not sufficient as a full account of life. This is a similar concern to that raised by proponents of autopoietic enactivism about a focus on operational closure in Varela's early account of biological autonomy (Di Paolo and Thompson, 2014). While recognising similarities between the two theories, Bickhard also maintains that there are important differences. Among other characteristics he contrasts his approach with the main characteristics of autopoietic enactivism – operational closure, precariousness and irreducibility of phenomenological experience. In autopoietic enactivism autonomy is tantamount to operational closure and precariousness. Bickhard notes that autopoietic enactivism misses the essential characterisation of living by not realising that both operational closure and precariousness are constituted by far from equilibrium conditions. Moreover, he observes that precariousness is already a normative term and, in contrast to his interactivism, the theory does not explain how such normativity emerges. Observer-dependent normative descriptions, to which autopoietic enactivism is committed, implies the existence of a gap between experiential and nonexperiential, which can only be addressed by correlational methods relating the first and the third person descriptions. In contrast, his account relates phenomenological and objective realms via various forms of emergence.

Montevil and Mossio build on Rosen's theory of biological organisation and view autopoiesis similarly to Bickhard (Montvil and Mossio, 2015). In particular, they note its lack of articulation of a distinction between biological closure and other forms of causal cycles present in nature. Although their focus is firmly on the roots of biological organisation and autonomy and hence they do not discuss autopoietic enactivism explicitly, the latter inclusion of precariousness as one of the defining features does not escape this objection, nor, being a normative term itself, does it allow for naturalistic account of emergence of normativity. In contrast, as Montevil and Mossio note, in his definition of (M,R)-systems, Rosen recognised the need to account for balance between closure and thermodynamic openness of biological organisation in considering two causal regimes. They also note that Rosen's formulation is very abstract, which may in part explain its relatively limited uptake. Consistent with Bickhard's insistence on grounding biological organisation in thermodynamics, Montevil and Mossio expand Rosen's construction by focusing on Kauffman's concept of the work cycle in which the circular relationship between work and constraints allows for a directed release of energy (Kauffman, 2000).

It is important to reiterate that the preceding discussion of Rosen's theory is based on only one of his definitions of living systems, (M,R)-systems, that explicated his views about the essential principles of biological organisation. It is his other definition of living systems, anticipatory systems, that provides a complementary account of the same organisation. The link between them has not been sufficiently explicated by Rosen and is often missed or underappreciated. Rosen contended that Newtonian physics, on which modern sciences are modelling their attempts at building formal models of their respective domains, deals with mechanisms which he considered simple systems. These, he contrasted with the organisms, which in turn he considered as examples of complex systems. Rosen's defining characteristics of complex systems is an existence of closed path of efficient causation. Thus, mechanisms, defined in terms of material, formal and efficient causes, can only approximate, but never fully replicate, complex systems, as the latter naturally entail the final cause or anticipation – a complex system may accommodate a model of itself and/or of its environment which it can use to modify its actions. In other words, complex systems entail anticipatory systems. Similar position has been expressed by Bickhard (2007). Even more interesting is a similar admission from Bechtel, one of the staunchest proponents of mechanistic explanation in biology (Bechtel, 2011). Specifically, Bechtel admits that mechanistic explanation coached in terms of sequential execution of operations may not be sufficient to account for the capacity of living organisms to maintain their distinct identity; here, the capacity is predicated on the presence of various feedback loops generating complex dynamics. He also states that progress in understanding such systems will require augmenting standard reductionist scientific methodology relying on decomposing the object of investigation into its constituent parts and operations (collectively mechanisms) by synthetic approaches that look back at the 'whole', perhaps using computer simulations.

Amongst the theoretical biologists concerned with characterisation of life, Rosen was in a sense most radical in his thinking as, not stopping at offering a critique of deficient modern science's explanatory power, he suggested a reformulation of its foundations by incorporating the Aristotelian notions of causality into its very framework. He starts from the premise that we need to extend our notion of causality used in scientific discourse to include the final cause in our descriptions of natural phenomena and consider mechanistic causality only as a very special case. In this view, anticipation becomes the most fundamental abstract characteristic of living systems, a building block enabling us to distinguish them in a systematic way from inanimate matter. For it is living systems that can drive their behaviour in anticipation of their futures, thus incorporating the final cause into their very essence, whereas inanimate matter is not capable of such behaviour, its dynamics

being fully determined by the present state and interactions. Thus, according to Rosen, physics, concerned with inanimate matter and phenomena, is a special case of such reformulated natural science and the extension going beyond physics can then include a proper account of living and cognition. This is in stark contrast to the currently prevailing view that physics is the most fundamental of the sciences with other sciences in principle, if not in practice, reducible to it. Interestingly, Kauffman, with his idea of adjacent possible and the ability of living systems to accommodate it in the way that is not mathematisable (at least within the framework of mechanistic Newtonian conception), (Kauffman, 2000), seems to grapple with similar ideas to those distilled by Rosen in his conception of anticipatory systems and their implications.

For more information about the enactivism please see (Thompson, 2007; Bishop and Martin, 2014; Di Paolo and Thompson, 2014; Stapleton and Froese, 2016; Stapleton and Thompson, 2009; Stewart et al., 2010), and for theories of biological autonomy the readers are referred to Letelier et al. (2011), Moreno and Mossio (2015). The next section will look at some evidence of anticipatory behaviour in the animal world and some of the critical evaluation of its account provided within traditional science.

4. Anticipation across scales

Theories of biological autonomy covered in Section 3 arise at the intersection of theoretical biology and philosophy. As such, they attempt to abstract away from specific examples of living systems and processes whilst trying to capture the overall principles and relate them to natural laws. They are not concerned with explaining or modelling specific phenomena encountered in the biological world, the latter constituting specific realisations. In this section the empirical evidence for anticipatory behaviour of biological organisms will be discussed, with examples drawn from more standard biological literature. Thus, the main aim of this section is not simply to motivate the theoretical models presented in Section 3, but to provide evidence that anticipation has to be understood in a more fundamental way than the usual cognitive and computational meaning of prediction or prospection ascribed to the term. Anticipation in its most basic form is a specific form of dynamical coupling between the system and its environment which can be observed already at a cellular level.

There is ample empirical evidence that organisms are using anticipation in their everyday activities. Memories and actions often concern future events and this in turn requires some form of anticipation. This has been recognised and studied in the psychology of both human and animal behaviour. In motor control studies, it has been recognised for some time that in order to provide timely and accurate responses animals cannot rely on operating in reactive mode only, due to the existence of noise and inevitable delays in information transfer between sensory surfaces, brain and actuators. This has been corroborated by the observation of early preparatory cortical activity occurring up to several seconds before an onset of voluntary action in the form of: so called bereitschaftspotential (BP), (Kornhuber and Deecke, 1965), event related desynchronisation/synchronisation (ERD/ERS), (Pfurtscheller and da Silva, 1999), or more recently as dynamical reorganisation (Wairagkar et al., 2014). Libet famously observed that such activity appears even prior to conscious intention to move, (Libet, 1985), a conclusion apparently supporting the deterministic and causal view of action generation but sitting uncomfortably with a concept of free will. The proposed solution for generation of appropriate motor commands was that the nervous system built so called forward models of the body and of the world. It was these models' predictions that enabled precise goal-directed movements to be executed (Shadmehr et al., 2010). There has been since a proliferation of accounts proposing internal models for motor control and trajectory planning including various control theoretic schemes seemingly supported by experiments coming from neurophysiological, imaging and behavioural studies (Kawato, 1999).

In fact, the need to account for prediction and internal models extends beyond mere motor control. As mentioned in Shadmehr et al. (2010), the idea that our perceptions are a result of combining evidence (sensory information) with prior beliefs about the state of matter, was considered already by Kant. Cognitive scientists came up with a taxonomy of different forms of 'orienting towards the future' (e.g. prediction, anticipation, expectation, prospection), (Nadin, 2013), that can be distinguished in cognitive processes and different dimensions along which predictive behaviour can be classified (Bubic et al., 2010). Many cognitive processes have been characterised from the perspective of prediction, (Bubic et al., 2010), or expectation (Huron, 2007). For example, anticipation appears especially important in music, where counterbalancing it with surprise is used by musicians for evoking emotional responses to their compositions (Huron, 2007).

Interestingly, the need to expand the reactive modelling to account for anticipatory processes has been steadily gaining traction in theories of physiological regulation (Sterling, 2004). There, the traditional model of homeostatic regulation determined thinking about physiology. It amounted to interpreting physiological regulation in terms of keeping the internal physiological variables set to some constant 'optimal' values by minimising their departures from the set point, treated as error terms. In contrast, allostasis proposes that the aim of the physiological regulation is to adjust the internal milieu to promote survival under natural selection. In order to achieve this efficiently, the regulation should prevent errors rather than minimise them; a change of emphasis embracing anticipation. In fact, allostasis has been originally proposed as the process of regulation of internal milieu in response to social interactions, placing it squarely as a physiological basis of social cognition (Schulkin, 2011). This should not be surprising, if one considers the complexity and variability of social interactions. Reactive (homeostatic) regulations would probably lag behind fast changing social context and anticipatory regulation of inherently slow feedback loops based on hormonal regulation may promote more meaningful social interactions.

Social cognition must arise from the intersection of neuroendocrine regulation and action understanding. The latter, in context of motion understanding, has been frequently accounted for by invoking the concept of a mirror neurone system, which is supposed to fire whether we engage in a motor action or simply observe the action in others. Although very appealing to the theories of social interaction, this is still a somewhat controversial concept attracting scrutiny of the collected data analysis, interpretation or consistency of the paradigm (Pascolo and Budai, 2013). One of the sticking points is timing. Pascolo's scrutiny of some of the original data from papers published by Rizolatti and Galese as well as his analysis of reaction times of top athletes suggest that the usual interpretation of embodied simulation (mirroring) should be replaced with action anticipation. This is a reinterpretation shared by Maldonato and Dell'Orco (2013) who contend that mirror neurones may be involved in anticipation of motor actions which confers on the other agency similar to that of the perceiver in lieu of shared motor repertoire and physical characteristics.

Anticipation is not exclusive to the animal world. Judith Rosen discusses a number of examples of anticipatory behaviour in plants (Rosen, 2009). What is more unexpected is that such behaviours seem to be also present in microorganisms such as bacteria, (Freddolino and Tavazoie, 2012; Mitchell et al., 2009), or yeast (Dhar et al., 2012). Dhar et al. (2012), discuss different mechanisms

that can help microorganisms orient towards the future. One of them is anticipation, where the unicellular organisms use the current environmental state to prepare themselves for the signalled imminent environmental change. *E. Coli*, for example, in response to an abrupt increase of ambient temperature starts expressing genes adaptive for a subsequent decrease in oxygen levels. Yeast exposed to heat stress is better prepared for the subsequent oxidative stress. Freddolino concludes that these examples indicate the limitation of the often invoked homeostatic principle and proposes a predictive dynamic framework to account for such cellular behaviour (Freddolino and Tavazoie, 2012).

Some remarks on microbial anticipation are in order. The problem with accounting for this phenomenon does not lie with homeostasis per se, which amounts to the ability to maintain steady internal state based on available information, but with the Newtonian conception of causality within which homeostasis is usually formulated. The same principle could as well be formulated with the organism including predicted future information in its attempts to maintain its internal state. Another observation is that in examples of anticipatory behaviour in microorganisms it seems anticipatory capacity amounts to microorganisms harnessing temporal correlations between different environmental variables. Such temporal regularities allow the organism to act in a reactive mode to the current state of the environment as if it actually used the future environmental states to determine the state of its gene regulatory network. This account shares some similarities with Rosen's definition of anticipatory systems. Applying his definition here, the model would be the microorganism's ambient temperature sensor and the causal entailments in the environment would amount to e.g. the movement of *E. Coli* through a digestive system. The system, the gene regulatory network, changes its state using information from the temperature sensor. However, anticipation here is a function of the dynamic coupling between the organism and the environment. This form of anticipation may appear when environmental regularities imply clear temporal correlations between different environmental variables; if an organism is able to harness such regularities, there is no need to generate an explicit internal prediction of the future environmental state. It seems plausible that similar mechanisms may account at least for some cases of plant anticipatory behaviour; a sentiment clearly shared by Louie (2010).

This brings about a number of questions about the types of anticipatory behaviours observed in nature. The preceding discussion describes very different situations and different organisms engaging in behaviours orienting themselves towards the future but the question of the underlying explanation need not always have the same answer. In what sense are predictions or expectations anticipatory? Must they always reduce to internal predictive models in Rosen's sense? Or perhaps in some circumstances is it possible that the organisms employ a weaker form of anticipation based on simulation? Does the empirical evidence confirm existence of internal predictive models directly or is the evidence only consistent with the functional outcomes of such models? After all, the existence of precise models may amount to a huge demand in terms of their implied capabilities and structure; simulations may be easier. First steps towards a taxonomy of anticipatory couplings and their possible occurrence in neural systems are discussed in Nasuto and Hayashi (2015).

Regardless of the potentially nuanced answers to the above questions, in the sciences operating within the traditional Newtonian framework, anticipatory behaviours are accounted for invoking 'models', which appear to be more akin to Rosen's definition of simulation (simulation and model are distinct in Rosen's theory; the differences are subtle although pivotal for Rosen's conclusions). Stepp and Turvey object to such representation hungry nature of predictive computational accounts in cognition (Stepp and Turvey, 2010). Troubled with computational models' inability to bridge the gap between low level and cognitive processes (even if they may appear, a posteriori, for any given data, as adequate descriptions), they propose to shift the emphasis from the representation-based predictive models to 'orienting towards the future' resulting from the coupling between the organism and its environment.

Bickhard takes into consideration theories postulating the brain's ability to generate predictions within probabilistic framework (Bickhard, 2016). Their scope has been extended to general theories of brain inference, most often claiming that brains perform a Bayesian inference. Typically, such 'predictive brain' theories rely on the generative probabilistic models for obtaining predictions of future states. Bickhard contends that such theories provide an inadequate account of the emergence of representation or normativity as, like in other computational and information processing models, these are arbitrarily imposed by the external observer rather than intrinsically emerging properties. Bickhard, too, postulates that the key to account for such properties is dynamic coupling or interaction between the organism and its environment and the organisms ability to anticipate interaction flow at different levels, with normativity emerging from the thermodynamic properties of the system.

Similar issues plague approaches attempting to account for motor control with the use of internal models. Theoretical control paradigms introduced in engineering are often defined in a way that is not guided by the modelling requirements of any specific process being observed – they are simply arbitrary recipes built in a modular way from blocks put together in such a way as to ascertain a desired trajectory of the control plant. The main prerogative of such an approach is ascertaining that the obtained control would provably enjoy pragmatically important characteristics, such as controllability, stability, robustness etc., which is feasible owing to universal design principles. This has to be contrasted with the dynamical systems approach to modelling coupled systems, where mathematical formalism is trying to represent the physical nature of coupling mechanisms first and foremost without imposing an *a priori* control theoretic model. Surely, we can impose control strategies onto the observed dynamically coupled systems, and often obtain a good fit to experimental data but this is more akin to (dynamic) statistical regression than to modelling the dynamical couplings from the first principles.

The emerging view from the current paper and the taxonomy of anticipatory processes (Nasuto and Hayashi, 2015), suggests that accounts based on dynamics of biological processes and their coupling to the external environments could have a better chance of capturing the essence of biological basis of cognitive processes, more so than computational interpretation of such processes which should generally come later. More specifically, after Rosen and others, it seems that very specific anticipatory dynamical couplings may constitute a fundamental mode of existence of living systems that is responsible for their distinctive properties, differentiating them from inanimate and inert matter.

The building blocks providing a basis for anticipatory coupling emerging from the discussion presented in Nasuto and Hayashi (2015) include

- predictive dynamics, and
- anticipating synchronisation.

They are based on somewhat different principles and offer appealing templates of the possible couplings that may be immune to the objections levelled at computational models or simulations, as discussed by Bickhard, or Rosen.

5. Animats – an experimental platform for cognitive robotics?

The question remains: where does this leave cognitive robotics? This section will highlight the possible future direction forward for robotic systems aimed at elucidating the most fundamental features of cognition.

The previous section pointed to the attractive characteristics of dynamic anticipatory couplings, which may form a bridge between mainstream empirical biology and some of the interesting theories of biological autonomy, as they are formed in terms of ingredients – dynamics, feedback and delays – commonly found in biological systems. They also prove attractive from the perspective of ecological psychology, (Stepp and Turvey, 2010), offering an intriguing possibility of a unifying account, converging with the aims of autopoietic enactivism.

The important issue to investigate is the role that such couplings may play and hence the need to test for their presence, role and implications. However, whether they, or some further yet to be identified processes, are constitutive elements of a biological autonomous system that is a living organism, is an empirical question that requires the right approaches and experimental paradigms.

Efforts to construct models of motor action focusing more on dynamic coupling than on representations, computations or control have already been pursued in the literature. Most notable have been the long standing efforts from Scott Kelso and his collaborators, who have been developing models of human motor control, (Kelso, 1997), or from Michael Turvey, one of the main proponents of ecological psychology and pioneers of dynamical approaches to motor coordination (Turvey and Fonseca, 2009).

The importance of dynamic couplings and coordination for social embodiment has been in recent years pursued by Tognoli et al. (2011). More recently, Hayashi proposed further extensions of Kelso paradigms to the case of mutual motion coordination based on a dynamic coupling between subjects engaged in the coordination task, (Hayashi and Sawada, 2013; Hayashi and Kondo, 2013), and as a result the interpretation of the motor coordination in terms of anticipating synchronisation has been put forward in (Blake et al., 2015).

Thus, there is a need for experimental platforms and an integrated cross-disciplinary approach allowing the combination of analytical and experimental research for the systematic manipulation of feedback loops and delays to investigate the existence, mode and processes constitutive of biological autonomy, including anticipatory couplings.

Such approaches lend themselves most easily to incorporation in robotic platforms as they do not require any specific hardware extensions or developments, only a particular modelling framework. Such research has already been ongoing in various robotic laboratories.

More recent developments in the form of animats – hybrid systems consisting of cultures of biological neurones controlling, in a closed loop, robotic bodies may start alleviating the apparent reluctance in the mainstream experimental biology to accept theoretical models of life and cognition as a fundamental framework for guiding the experimental paradigms and interpreting results. They have a potential to blend the research in cellular and systems neuroscience, thus allowing to address the questions on biophysical and metabolic underpinnings of neural processes, with approaches typical in cognitive robotics, exploring the role of embodiment and closed loop interactions with the environment. Steve Potter's group was one of the first to pioneer this platform (DeMarse et al., 2001; Bakkum et al., 2004). Few groups have also pursued this line of research (Shahaf et al., 2008; Novellino et al., 2007; Tessadori et al., 2012; Warwick et al., 2010).

It is worth emphasising here that in spite of the presence of a real biological culture controlling, in a closed loop, a robotic device, current animat platforms do not yet escape criticisms levelled against cognitive robotics, as the construction of the closed loop of these systems still conforms to a formal mechanistic and externally arbitrarily interpretable computation, and they suffer lack of closure to efficient causation (Nasuto and Bishop, 2012).

In spite of this negative result, the animat nevertheless offers a very promising experimental platform for investigating fundamental questions about the nature of cognition. The animat platform developed by the University of Reading group uses multiple electrode arrays (MEA) which offer a bidirectional link allowing to record activity and stimulate cultures of real biological neurones grown on them. The information to and from the culture is routed via TCP/IP protocol to a computer analysing it and conveys instantaneous neural culture activity which is translated in real time into the actuation of a robotic device. The actuators' commands are sent to the robot via wireless link and the resultant change of the robot's state translates into concomitant changes of its sensor readings, as the robot probes the environment while exploring it. The sensory information is routed back to the MEA headstage and is there converted into the electrical stimulations delivered via the MEA electrodes to the culture, thus closing the feedback loop. The 64 MEA electrodes offer a possibility to investigate meso-scale processes, including the spatiotemporal patterns of activity and their modifications due to maturation, or electric or chemical stimulation. This offers an excellent opportunity to have very good access to the neural system and to investigate the processes that may confirm, or disprove, the existence of particular constituent characteristics of biological autonomy.

The culture activity, though complex, is not entirely random in spite of the seemingly random nature of its structural connectivity (Downes et al., 2012). In fact, the functional connectivity patterns seem to follow a specific progression as the culture matures exhibiting the emergence of small world networks. The complex networks corresponding to functional connectivity are not static but undergo complex dynamic transitions (Spencer et al., 2010, 2011, 2012). Thus, already such simple neural systems show the organisational capacity that Singer proposed to be underpinning the relational codes, (Singer, 1999), and Varela postulated as underlying conscious perception (Varela et al., 2001).

The spatiotemporal patterns of culture activity also show hallmarks of transient metastable state transitions (Xydas et al., 2011). This may be the complementary characteristic of evolving complex network dynamics and may allow for flexible switching between different behaviour patterns or percepts, which are the most consistent with the incoming input (Kelso, 1997).

As highlighted earlier, in addition to the characterisation of organised mesoscale electrophysiological activity, the animat platform also allows to interrogate the neurobiological properties of cultures using standard neuroscience approaches. To this end, the presence and responses of cholinergic synapses characterised by our group Hammond et al. (2013), also indicate a nonrandom arrangement akin to that found *in vivo*. Acetylcholine is an interesting chemical used in the brain as both neurotransmitter and neuromodulator, i.e. it is able to contribute to transmission of information at chemical cholinergic synapses as well as to modulate such transmission at other synapses. Emergence of functional cholinergic circuits may indicate that the cultures retain potential to support cognitive processes in which acetylcholine has been implicated, such as memory or attention. This opens an exciting prospect of future experiments, in which the relative role of, and interactions between, the closed loop environmental coupling via animat robotic body and the cholinergic system modulations of culture activity can be explored.

6. Conclusions

Given their entrenchment in a Newtonian mechanistic framework, neither current cognitive robotics nor biology or classical cognition can escape the mechanistic dead end.

The problems with the computational accounts of cognition, including a hybrid analogue-discrete one of the cognitive robotics ilk, are inherited from the dualistic conception of reality developed in western philosophy and, at least in part, from the mechanistic Newtonian causality developed in physics that is widely accepted as the ultimate explanatory methodology for inanimate and as well as living systems.

The apparent congruence of computational accounts with the classical physics framework may explain why the computational theories of mind are so dominant. Another, but not unrelated, reason is epistemological. The traditional sciences are typically so focused on looking into the past and describing what has already happened in order to account for data that have been collected in very specific circumstances, that the need to account for the capacity of organisms to deal with novel, future hence unconstrained situations, where the mechanism of anticipation can actually be properly assessed, has been largely exercised away from the traditional scientific experimental paradigm. We need to rethink both the foundations and the mode of collecting experimental evidence in order to start closing the gap between the theoretical concept of anticipation and scientific practice in experimental sciences.

The theory put forward by Rosen and others, if true, offers a way out. By properly accounting for the living organisms' ability to 'orient themselves towards the future', through exploiting the anticipatory couplings and appropriate systemic complexity, it offers a framework that may be able to reconcile philosophy with science into a complete explanatory natural science.

In order to fulfill its ambitions, cognitive robotics will have to move beyond the current hybrid symbolic-analogue computational framework and platforms and embrace new platforms that may enable it to elucidate the nature of autonomy and goal oriented behaviour. Animats, part-neurobiological, part-robotic hybrids, belong to a class of experimental platforms offering ability to combine experimental approaches used in traditional cellular neuroscience, with investigation of mesoscale level dynamics of neural systems and sensorimotor accounts characteristics of cognitive robotics. It is this ability for simultaneous probing of different levels of embodiment and their mutual interactions that offers exciting possibility to advance our understanding of natural autonomy and the biological basis of cognition.

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